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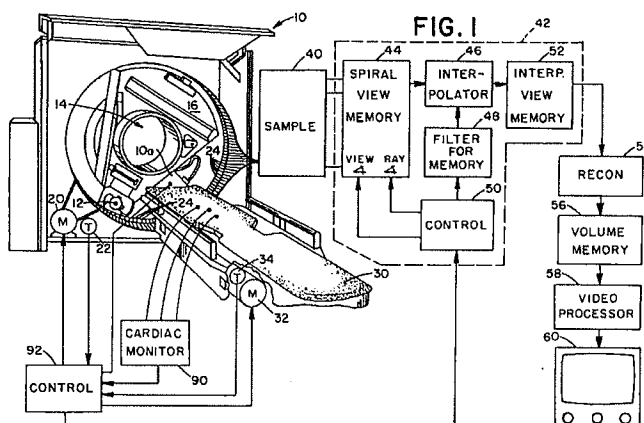
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Imaging apparatus and methods.

A radiation source (12, 216) rotates around a patient on a patient couch (30, 212) as the couch is advanced through an examination region (14, 214). Radiation detectors (24, 230) detect radiation that has passed through the patient along rays of a plurality of fan shaped views. Each view is identifiable by its angular position ϕ around the examination region and its longitudinal position R in the spiral and each ray is identifiable by its angular position β in the fan. An interpolator (46) interpolates views collected over more than two revolutions of spiral path using an interpolation function (62, 94). A set of interpolated views is reconstructed (54, 250) into a series of image representations representing parallel planar slices through the imaged volume. In some reconstructions, particularly reconstructions in which a 180° based reconstruction algorithm is used or the energy of the x-ray beam is varied, the filter function (82, 84, 86, 116, 118) is varied from ray to ray within each view. A projection filter can also be varied from view to view in order to emphasize structures along various axes of a subject. A cardiac or other physiological condition monitor (90) monitors for movement of the subject so that one or more of the rotational speed of the x-ray source (12, 216), movement of the patient couch (30, 212), energy of the x-ray beam, or filter function can be varied accordingly.



This invention relates to imaging apparatus and methods.

It finds particular application in the reconstruction of spiral volume images using computed tomography (CT) scanners and will be described with particular reference thereto. However, it is to be appreciated that the invention will also find application in conjunction with other types of volume imaging, with multiple single
5 slice images, continuous rotating x-ray source images, gated imaging, and the like.

In spiral or helical scanning, the x-ray source or tube rotates continuously as the patient support table moves at a constant, linear velocity. In this manner, the collected data effectively represents a helical path of constant pitch through the patient. Conventionally, the data is stored and handled as a series of parallel planes, transverse to the longitudinal axis of the patient, or more specifically, as a three dimensional
10 rectangular matrix of memory cells as described in U.S. Patent No. 3,432,657.

In order to fit the spiral collected data into a conventional three dimensional rectangular matrix, a series of parallel planes are defined through the spiral collected data, with a one plane per spiral revolution, e.g. at each 0° of source rotation. During the data collection period, a series of views or fans of data are collected at preselected angular increments around the patient. Potentially, one view per plane, by convention the 0°
15 or 12 o'clock view, falls squarely in the plane requiring no averaging or weighting. For each remaining view of the plane, there is a pair of corresponding views or data fans, one from the revolution preceding the plane and the other from the revolution following the plane. These views are averaged or weighted in accordance with their relative distance from the plane. In this manner, a full set of weighted views is created to perform a conventional 360° CT reconstruction algorithm. See U.S. Patent No. 4,630,202 issued
20 December 1986 to Mori and U.S. Patent No. 4,789,929 issued December 1988 to Nishimura, et al.

One of the problems with the spiral scanning techniques is that excessive partial volume artifacts were caused in certain applications. Another problem is that the linear interpolation or weighting is only applicable to 360° based revolution reconstruction techniques, not 180° plus fan reconstruction algorithms. See U.S. Patent No. 4,293,912 issued October 1981 to Walters.

Another problem with the linear interpolation technique is that it introduces errors in fourth generation scanners using source fan reconstruction. In a third generation scanner in which the x-ray source and an arc of detectors rotate together about the slice, each data fan or view is collected instantaneously in a plane parallel to the artificially defined transverse slices. In a fourth generation scanner, there is a parallel ring of stationary detectors surrounding the patient. With source fan reconstruction, each detector is sampled at
30 monitored, time displaced intervals generating a view or fan of data as the source rotates behind the examination region. Because the patient moves longitudinally between the first and last data sampling of the view or data fan, the views are warped or canted along the spiral path. The linear interpolation scheme which assumes that the views lie parallel to the artificially defined planes introduces errors.

Another problem with the linear interpolation technique is that it is particularly sensitive to variations in
35 the x-ray rotation speed, the velocity with which the patient is moved, and fluctuations in the output of the x-ray tube.

Continuous rotation of the x-ray source with a stationary patient has been utilized for gated scanning. See for example U.S. Patent No. 4,868,748 issued September 1989 to Mori. In this technique, the patient remains stationary and the x-ray tube continuous to rotate in the same plane of the patient. In response to
40 the R-wave of the patient's cardiac cycle, the x-ray tube or its shutter is gated on to collect a view of data. In this manner, data is collected over a plurality of cardiac cycles for constructing a stop-action slice through the patient's heart. Of course, this technique is not amenable to spiral volume imaging.

Another prior art CT scanner imaging technique includes the generation of two reconstructed images through the same slice but with different energies. The two different energy images could be collected
45 concurrently by pulsing the x-ray tube alternately at high and low energy levels to collect the high and low energy views alternately. See "Generalized Image Combinations in Dual KVP Digital Radiography", Lehmann, et al., Med. Phys. 8(5), Sept./Oct. 1981. Alternately, the two images could be collected sequentially, i.e. all of the views of the low energy image followed by all of the views of the high energy image as described in "Evaluation of Prototype Dual-Energy Computed Tomographic Apparatus, I Phantom
50 Studies", Calendar, et al., Med. Phys. 13 (3) May/June 1986 and "Evaluation of Prototype Dual Energy Computed Tomographic Apparatus II Determination of Vertebral Bone Mineral Content", Vetter, Med. Phys. 13 (3) May/June 1986. However, each of these techniques required two rotations per slice, one rotation to collect the low energy image data and one rotation to collect the high energy image data or one rotation to collect half the low energy and half the high energy image data and a second rotation to collect the other
55 half of the low energy and the other half of the high energy image data. Because two revolutions per image set are required, the prior art dual energy imaging techniques are not suited to linear weighted helical scanning.

It is an object of the present invention to provide a new and improved imaging apparatus and method.

According to a first aspect of the present invention there is provided a method of imaging including the step of: moving a radiation source and a subject relative to each other so as to irradiate the subject along a generally spiral path; and characterised in that said method further includes the steps of collecting a plurality of views of image data, each view being identifiable by an angular position around the subject and
 5 by an axial position along a spiral; interpolating corresponding views collected over more than two revolutions along generally spiral paths; and reconstructing the interpolated views into a plurality of image representations corresponding to a plurality of parallel slices through the subject.

According to a second aspect of the present invention there is provided a method of imaging including the step of: moving a subject and a radiation source such that the subject is irradiated along a first
 10 generally spiral path; characterised in that it further includes the steps of collecting a plurality of views of data each identifiable by its position along said spiral path; interpolating longitudinally corresponding views with an interpolation function; and, reconstructing groups of views which nominally span less than 360° into a plurality of parallel planar image representations corresponding to a plurality of parallel slices of the subject.

According to a third aspect of the present invention there is provided a method of imaging including the step of: moving a subject and a radiation source such that the subject is irradiated along a generally spiral path; and characterised in that it further includes the steps of collecting a plurality of views of data, each view being defined by a plurality of rays or radiation meeting at an apex with each view being identifiable by an angular position of the apex along a spiral; filtering rays within the views with each of a multiplicity of
 20 filter functions, each filter function being selected in accordance with the angular position of the view and an angular position of the ray within the view; and reconstructing the views into a plurality of parallel image representations.

According to a fourth aspect of the present invention there is provided a method of imaging including rotating a source of radiation around a subject; characterised in that it further includes converting radiation
 25 which has traversed the subject into a plurality of views, each view including a fan shaped array of radiation paths with an apex of each fan shaped array disposed at an identifiable angular position around the subject; monitoring for a preselected cyclic event in the subject; controlling rotational movement of the radiation source to synchronize the source rotation and the monitored cyclic event; and reconstructing the views into at least one image representation.

According to a fifth aspect of the present invention there is provided a method of imaging including the step of: rotating a source of radiation around an examination region; and characterised in that it further includes the steps of detecting radiation which has traversed the examination region to collect a plurality of views of data, each view being identified by an angular position around the examination region; filtering each view with one of a plurality of filter functions selected in accordance with the angular position of the
 30 view around the examination region; and reconstructing the views into at least one image representation.

According to a sixth aspect of the present invention there is provided a method of imaging including the steps of: moving a radiation source and a subject relative to each other such that the radiation source irradiates the subject generally along a spiral; concurrently detecting radiation which has traversed the patient to collect views of data; filtering collected data views; reconstructing the filtered data views into a
 40 plurality of image representations representing parallel displaced planes characterised in that at least two longitudinally spaced arcs of detectors detect said radiation to collect views of data lying along at least two interleaved spiral paths.

According to a seventh aspect of the present invention there is provided a method of imaging including the steps of: rotating a source of radiation around a subject in an examination region; detecting radiation
 45 which has traversed the subject to collect views of data, each view having an apex at an identifiable angle around the subject and each view including a fan shaped array of radiation beams which has traversed the patient; filtering the views, using a filter function; reconstructing the views into at least one image representation characterised in that it further includes varying, while the source of radiation is rotating, an energy of the radiation source between at least two energy levels.

According to an eighth aspect of the present invention there is provided a method of imaging including the steps of: rotating a source of radiation around an examination region; moving a subject through the examination region; characterised in that it further includes the steps of monitoring at least one of (i) the rotation of the radiation source, (ii) longitudinal movement of the subject, and (iii) an energy of the radiation source; converting radiation which has traversed the subject into a plurality of views, each view including
 50 data collected from a fan shaped array of radiation rays with an apex of each array disposed at an identifiable angular position around the examination region; filtering each view with a filter function; controlling at least one of the rotation of the radiation source, the longitudinal movement of the subject, an energy of the radiation source, and the filter function in accordance with the monitoring step; and

reconstructing the filtered views into at least one image representation.

According to a ninth aspect of the present invention there is provided an imaging apparatus including: means for moving a radiation source and a subject relative to each other so as to irradiate the subject along a generally spiral path; and an arc of radiation detectors for receiving radiation which has traversed the subject; characterised in that it further includes means for assembling radiation detected by the radiation detectors into a plurality of views, each view being identifiable by an angular position around the subject and an axial position along a spiral path; interpolating means for interpolating angularly corresponding views collected over more than two revolutions around generally spiral paths; reconstructing means for reconstructing the interpolated views into a plurality of image representations; and memory means for storing the plurality of image representations.

According to a tenth aspect of the present invention there is provided an imaging apparatus including: means for moving a subject and a radiation source such that the subject is irradiated along a generally spiral path; and at least one arc of radiation detectors for detecting radiation from the source which has traversed the subject; characterised in that it further includes means for assembling detected radiation into a plurality of views, each view having data generated from radiation that traversed the subject along a plurality of rays, each ray having an identifiable angular position within a view and each view being identifiable by an angular position around a spiral path and a longitudinal position along the spiral path; filtering means for filtering views identified by the same angular position with a filter function; reconstructing means for reconstructing groups of views, which nominally span 180° , into a plurality of image representations; and memory means for storing the plurality of image representations.

According to an eleventh aspect of the present invention there is provided an imaging apparatus including: a source of radiation; means for rotating the source of radiation around a subject; and at least one arc of radiation detectors for converting radiation from the source which has traversed the subject into a plurality of views, each view including data converted from a fan shaped array of radiation rays with an apex of each fan shaped array disposed at an identifiable angular position around the subject; reconstructing means for reconstructing the views into at least one image representation; characterised in that it further includes subject monitoring means for monitoring a preselected cyclic movement of said subject; controlling means operatively connected to the radiation source rotating means and the monitoring means for controlling relative rotation of the source in accordance with the monitored cyclic movement; reconstructing means for reconstructing the views into at least one image representation; and memory means for storing the at least one image representation.

According to a twelfth aspect of the present invention there is provided an imaging apparatus including: subject supporting means for supporting a subject in an examination region; a radiation source for irradiating a portion of the subject in the examination region with penetrating radiation; means for rotating the radiation source around the examination region; means for longitudinally advancing the patient supporting means through the examination region at a generally constant velocity; means for detecting said radiation; means for assembling the detected radiation into a plurality of views; filtering means for filtering the views; reconstructing means for reconstructing the filtered views into a plurality of image representations; and memory means for storing the image representations; characterised in that said means for detecting said radiation comprises at least two parallel arcs of radiation detectors disposed generally parallel to a path of radiation from said source for concurrently detecting radiation which has traversed the subject along at least two longitudinally spaced arcs; and each view is identifiable by an angular position relative to the subject and a longitudinal position along at least two interleaved spiral paths around the subject.

According to the thirteenth aspect of the present invention there is provided an imaging apparatus including: a source of radiation; means for rotating the source of radiation around an examination region; radiation source energy control means for controlling an energy output of the radiation source; at least one arc of radiation detectors for detecting rays of radiation which have traversed the subject; means for assembling detected radiation into a plurality of views, each view representing rays meeting at an apex at an identifiable angle within the examination region; reconstruction means for reconstructing the views into an image representation; characterised in that the radiation source energy controlling means causes the radiation source energy to vary between at least two energy levels.

According to a fourteenth aspect of the present invention there is provided an imaging apparatus including: a source of radiation; radiation source energy control means for controlling an energy of radiation generated by the radiation source; means for rotating the radiation source around an examination region; means for advancing a patient supporting means longitudinally through the examination region; at least an arc of radiation detectors for detecting rays of radiation from the source which has traversed the examination region; characterised in that it further includes: means for organizing radiation detected by the

radiation detectors into a plurality of views, each view representing a fan shaped array of radiation rays with an apex of the array disposed at an identifiable angular position within the examination region; filtering means for filtering the views with a filter function; monitoring means for monitoring at least one of a speed of radiation source rotation, a speed of the patient supporting means longitudinal advancement, and an energy of the radiation source; means operatively connected with the monitoring means for controlling at least one of the speed of rotation of the radiation source, the speed of longitudinal advancement of the

views into image representations; and memory means for storing the image representations.

According to a fifteenth aspect of the present invention there is provided an imaging apparatus including: a source of radiation; means for rotating the source of radiation around an examination region; means for determining an angular position of the source of radiation around the examination region; at least one arc of radiation detectors for detecting radiation from the radiation source that has traversed the examination region; means for assembling the detected radiation into a plurality of views; filtering means for filtering each view with a filter function; reconstructing means for reconstructing the views into at least one image representation; memory means for storing the at least one image representation; characterised in that each view is identifiable by an angular position within the examination region and in that said apparatus comprises filter function selecting means for selecting a filter function corresponding to the angular position of each view.

According to a sixteenth aspect of the present invention there is provided an imaging apparatus including a source of penetrating radiation; means for rotating a source of radiation around an examination region; means for advancing a subject through the examination region; at least one arc of radiation detectors for detecting radiation from the radiation source that has traversed the examination region; means for organizing the collected radiation into a plurality of views of data; filtering means for filtering data representing each ray of each view with a filter function; reconstructing means for reconstructing the image representations from the views; memory means for storing the image representations; characterised in that each view represents a plurality of rays of radiation extending in a fan shaped array from an apex at an identifiable angle around the examination region; and in that said filter function is selected in accordance with the identifiable angle of the view within the examination region and an angle of each ray within the corresponding view.

One advantage of the present invention is that it provides for faster volume scanning.

Another advantage of the present invention is that it facilitates dual energy volumetric scanning.

Another advantage of the present invention is that the scanning technique can be synchronised with cyclic physiological movement of the patient.

Another advantage is that the effects of variations in the radiation source rotation speed and in the speed of movement of the patient can be minimized.

Another advantage is the longitudinal image quality is improved and partial volume effects are minimized.

One imaging apparatus and imaging methods in accordance with the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:-

Figure 1 is a diagrammatic illustration of one embodiment of the imaging apparatus in accordance with the present invention;

Figure 2 illustrates the geometry of the examination region within the imaging apparatus;

Figures 3A-3E illustrate within the imaging apparatus different linear weighting functions;

Figures 4A and 4B illustrate interpolation or weighting functions for 180° based reconstruction algorithms;

Figures 5A-5D illustrate compensations for gantry rotation and table speed variations and, in particular, of variations in weighting functions for effecting the compensation; and

Figures 6A-6C illustrate x-ray current and kV fluctuations and corresponding weighting functions for dual kV imaging techniques.

Referring to Figure 1, the apparatus includes a computed tomography scanner 10 incorporating a radiation source 12, such as an x-ray tube, for projecting a fan beam of radiation through an examination region 14. The x-ray tube is mounted on a rotatable gantry 16 to rotate the fan beam of radiation around the scanned circle. A collimator and shutter means 18 collimates the beam of radiation to one or more narrow planar beams and selectively gates the beam on and off. The beam may be also gated on and off electronically at the x-ray tube 12. A motor 20 provides motive power for rotating the gantry 16 continuously around the examination region. A rotational position encoder 22 is connected with the motor and the gantry to measure the rotational position of the gantry.

In the illustrated fourth generation CT scanner, a ring of radiation detectors 24 are mounted peripherally

around the examination region. For mechanical and mathematical convenience, the detectors 24 are stationarily mounted around the rotating gantry in the same plane as the x-ray tube. With reference to Figure 2, an arc of detectors is sampled concurrently at short time increments as the radiation source 12 rotates behind the examination region 14 to generate views or fan data sets. To generate detector fan data sets, an exemplary detector 26 at an angular position 0 is first sampled when the radiation source is at a location 28a tangent to one side of the examination region 14 and monitored incrementally until the radiation source reaches a point 28b in a line from the detector tangential to the other side of the examination region. For a source fan geometry, each of the detectors between detectors 26a and 26b are sampled concurrently to generate a source fan view or data set. The collected source fan data set can be identified by the angular position ϕ of its apex around the examination region. Each ray of data between the source and one of the detectors is described by an angle β . Each ray of the source fan is also identifiable by its angle gamma (γ) relative to the common axis. The source is disposed a radius S from the center of the examination region and the ring of detectors 24 is disposed a radius D from the center of the examination region. In a third generation scanner in which the invention is equally applicable, a single arc of detectors between detectors 28a and 28b is mounted to the gantry 16 for rotation with the source. The third generation source fan geometry is described mathematically in the same way.

With reference again to Figure 1, a patient couch 30 supports a subject, particularly a human patient, in a reclined position. A means such as a motor 32 is provided for advancing the patient supporting surface of the couch through the examination region at a selectable velocity. An encoder 34 is connected with the motor 32, the moveable patient supporting portion 30, and the drive mechanism therebetween for monitoring the actual position of the patient supporting surface as it moves the patient through the examination region 14.

A sampling means 40 samples the views or data sets corresponding to each angular position ϕ around the examination region 14 for each of a multiplicity of x-ray source rotations. A view processor 42 converts the spiral sampled views into a plurality of image representations corresponding to parallel planes. The view processor includes a view memory 44 in which the view data is stored and is addressable by a combination of the rotation number R, view angle ϕ , and ray angle β within the view. The view processor 42 further includes a filter or interpolation means 46 for interpolating the spiral data in the spiral view memory 44 into parallel slice data. The interpolation means 46 operates on a plurality of views of corresponding view angle ϕ with a filter or interpolation function supplied by a filter function memory 48.

A control means 50 indexes the view angle ϕ to each of the view angles in a complete set of views, e.g. the views disposed at regular increments 360° around the examination region. A plurality of views corresponding to each individual view angle ϕ are transferred to the interpolation means to be filtered into an interpolated view. Each interpolated view is stored in an interpolated view memory means 52 until a full set of views for reconstruction is generated. Thereafter, an image reconstruction means 54 uses a conventional filtered backprojection or other reconstruction algorithm to reconstruct each of a plurality of slices and store the resultant slices in a volume data memory means 56. The volume data memory means stores a rectangular pixel array corresponding to each of a plurality of slices, the slices being spaced a distance commensurate with the resolution of the pixels in each slice. In this manner, the data in the volume data memory means can be conceptualized as a rectangular data volume. A volume memory access means and video processor 58 accesses selected memory cells of the volume data memory means 56 to withdraw radiation attenuation or absorption information representative of a corresponding volume or surface through the patient and converts such information into a video signal for display on a display means 60 such as a video monitor.

With reference to Figure 3A, the interpolation function memory means 48 stores a plurality of filter or interpolation functions. Figure 3A compares a modified linear weighting function 62 with a prior art linear weighting 64. The modified linear weighting function $W(\phi) = 0$ for $|R| > 1.5$ with an average width of 1.1, where $\phi = R \cdot 360^\circ$, R being the rotational index or longitudinal position. $W(\phi)$ and its first derivative are both continuous as is represented by the rounding adjacent $R=0$ and $R=+1$. The rotational index R is the sum of the integral rotation index m and the fractional rotation index r. Moreover, the weighting function has unity weighting i.e.

$$\sum_{r=0}^1 W(\phi_r) = 1, \text{ for } 0 < r < 1 \quad (1)$$

where

$$\phi_m = (r+m)360^\circ$$

and the first moments are equal to zero, i.e.

5

$$\sum_m (r+m) \cdot W(\phi_m) = 0, \text{ for } 0 < r < 1 \quad (2).$$

10 In FIGURE 3B, a cubic weighting function 66 which spans four contiguous rotations is compared with the conventional linear interpolation 64. In the cubic interpolation,

$$W(\phi) = 0, \text{ for } |R| > 2 \quad (3)$$

15 with an average width ≈ 1.1 . $W(\phi)$ and its first derivative are again continuous and the conditions of Equations (1) and (2) are also valid. Analogously, a cubic weighting of the form 68 may also be utilized where

$$W(\phi) = 0, \text{ for } |R| > 3 \quad (4)$$

20

and with a width (at half height) equal to 1.6 rotations.

FIGURE 3C compares the conventional linear weighting 64 with a 7-lobe helical weighting function 70 where:

$$25 \quad W(\phi) = 0, \text{ for } |R| > 4 \quad (5)$$

Again, the function and its first derivative are continuous and the conditions of Equations (1) and (2) are met.

30 With reference to FIGURE 3D, the conventional linear weighting of curve 64 has a relatively limited frequency response 72 along the z-axis. By distinction, the 7-lobed helical weighting function 70 has a much crisper frequency response 74 in the z direction. Note that the frequency response of the 7-lobed helical weighting 74 is relatively flat and drops off relatively quickly which eliminates the smoothing heretofore required with the linear weighting function.

35 It should be noted that the rotational index or longitudinal position R in FIGURES 3A-3D is not measured digitally. That is, if the detector crosses the even integer values $R = 0, \pm 1, \pm 2$, etc., at 0° , then at 90° , the R position is $-.75, +.25, +1.25$, etc.

40 In accordance with another embodiment of the present invention, the reconstruction means 54 uses a reconstruction algorithm based on views spanning 180° plus the fan angle, such as the algorithm illustrated in U.S. Patent No. 4,293,912 issued October 1981 to Walters. To utilize the 180° redundancy in the data most effectively with interpolation functions of the shapes described above but of half the extent, the interpolating filter from filter memory 48 is redefined on a 180° basis. Specifically, the linear weighting 64 would result in a warped rather than a planar image representation.

45 With reference to FIGURE 4A, a preferred technique for using 180° basis reconstruction techniques is to use a weighting function based on both the view angle γ and the angle β of each individual ray within the view. Curve set 80 includes the modified linear function 62 for the center or zero ray of the view or fan. Curve 82 illustrates the modified weighting function shifted for the ray at one extreme of the fan and curve 84 illustrates the modified weighting function shifted for the ray at the opposite extreme of the fan. For each ray in between, the extreme and central rays, the weighting function is shifted a fraction of the illustrated difference. Each weighting curve and its first derivative are still continuous but now meet the conditions of
50 Equations (6) and (7) below. The sum of the weighting functions for rays which are 180° opposite to each other is equal to one.

$$55 \quad \sum_m W(\gamma_m, (-1)^m \beta) = 1, \text{ for } \gamma_m = (r+m)(180^\circ) \quad (6)$$

Also, the first moments are equal to zero, i.e.

$$\sum_m \left(\gamma + m + \frac{(-1)^m \beta}{180} \right) \cdot W(\gamma_m, (-1)^m \beta) = 0 \quad (7)$$

5 For projection data organized in the form of source fans

$$V_s(\phi + n \cdot 360^\circ, \beta),$$

the longitudinal interpolation generates:

10

$$D_{180}(\phi, \beta) = \sum_n W_s(\phi + n \cdot 360^\circ, \beta) \cdot V_s(\phi + n \cdot 360^\circ, \beta) \quad (8a)$$

15

where:

$$W_s(\phi + n \cdot 360^\circ, \beta) = W(\gamma + \beta, \beta)$$

20 and $W_s(\gamma, \beta)$ is the weighting function that satisfies conditions (6) and (7).
and $\phi = 0$ to 360°

$$\beta = -\frac{\beta_o}{2} \text{ to } \frac{\beta_o}{2}$$

25

β_o = fan angle defining the scan circle 14.

30 The resulting 360° of projection data $D_{180}(\phi, \beta)$ no longer has unity weighting, but instead has an average weighting spanning 180° . This data can be reconstructed using standard convolution backprojection of $D_{180}(\phi, \beta)$ for $\phi = 0$ to 360° . For projection data organized as detector fans $V_D(\theta + n \cdot 360^\circ, \alpha)$, the longitudinal interpolation generates:

$$D_{180}(\theta, \alpha) = \sum_n W_D(\theta + n \cdot 360^\circ, \alpha) \cdot V_D(\theta + n \cdot 360^\circ, \alpha) \quad (8b)$$

35

where

α is the angular position of the ray within the detector fan

and

40 $W_D(\theta + n \cdot 360^\circ, \alpha)$ is obtained by remapping

$W_s(\phi + n \cdot 360^\circ, \beta)$ from source fan format to detector fan format. Again, this data can be reconstructed using standard convolution backprojection of $D_{180}(\theta, \alpha)$ for $\theta = 0$ to 360° .

45 Analogously, the weighting function $W_{180}(\gamma, \beta)$ for the cubic weighting function of curve 66 of FIGURE 3B can be made ray dependent as illustrated in FIGURE 4B. Specifically, cubic weighting function 66 is used for the central ray. For the ray at one extreme, the weighting function is distorted as illustrated by curve 86 and for the ray of the other extreme of the fan, the weighting curve is distorted as illustrated at 88. In the illustrated embodiment, the extreme rays of curves 86 and 88 are for $\beta = \pm 23^\circ$.

50 Looking to another aspect of the invention, the reconstruction filter function 54 may also be varied on a view angle ϕ and ray angle β basis to vary the frequency content of the projections. For example, the torso of a human subject is generally an oval that is significantly wider than it is high. The path length through the patient for some rays is significantly longer than for others. In accordance with another aspect of the present invention, the cross sectional size and shape of the patient are measured to determine the relative path length for each view and ray angle. Alternately, the ray lengths for one or more standardized cross sections can be calculated and stored and the most nearly accurate cross section selected. The bandwidth
55 of the filter function is adjusted generally in proportion to the ray length through the subject. In an oval human torso, projections around 0° or straight over head are filtered the least and those near $+90^\circ$ are the most highly filtered. Analogous advantages can be obtained by varying the filter function with the view angle ϕ only.

As shown in Figure 1, a cardiac or other cyclic physiological movement monitor 90 and the encoders 22 are interconnected with a rotation control means 92. The rotation control means controls the motor 20 such that the x-ray source 12 rotates synchronously with the normal cardiac cycle of the patient. More specifically to the preferred embodiment, the x-ray source 12 is at the same preselected angular orientation at the same preselected point in each cardiac cycle.

Synchronization of the movement of the source 12 with cardiac and other cyclic patient movements is advantageously utilized in conjunction with the angle dependent filtering technique. By lightly filtering views with the heart in one preselected phase and more heavily filtering views taken when the heart is in another phase, blurring of cardiac and cardiac relation motion is diminished. With appropriate filtering, a substantial freeze action of the heart may be obtained. Of course, movement of the source 12 may be synchronized with other subject movement. In this manner, reconstruction is biased towards planes with the minimal filtering. When the minimal filtering is at 0° or straight above, imaging in the sagittal or coronal plane is enhanced and degrading motion is minimized.

This technique is also applicable to performing rapid scans to watch the advancement of a contrast agent injected into the patient. As an example of one specific implementation, the patient is moved in a first direction to create one helix of data and then moved in the other direction to create a second crossing helix in the opposite direction covering the same volume. This minimizes the delay between passes but does not provide time information for a given slice in equal intervals. In a second embodiment, a steep pitch helix is selected, for example, one which collects only about half the normal number of views. The patient may then be shifted back to the beginning and the other half of the views are collected along a second helix. This process may be repeated again and again to collect half data sets at close time displaced intervals. Image data may be reconstructed, combining time adjacent data sets into a complete data set to provide a series of time incremented volume images to watch the migration of the contrast agent through the patient, or other physiological changes. When the corresponding views are longitudinally taken in different passes, it is preferred that one of the longer longitudinal weighting functions be applied, such as the 7-lobe helical weighting function 70 of Figure 3C. Note, the ends of each pass are processed with a shortened weighting function for imaging the end slices. For even faster scanning, this technique is advantageously utilized with a 180° basis reconstruction algorithm and weighting functions discussed above.

The control means 92 is also connected with the encoder 34 such that movement of the patient supporting table is coordinated with rotation of the x-ray source. As the speed of rotation of the x-ray source 12 and the velocity of table movement change, the relative weighting of the views is also altered. Note that a given helix can be maintained at proportionally higher source rotation and patient advancement rates but the radiation dose per view and sample intervals changes. These variations in speed can also produce a scanning path which is non-helical. Analogous problems arise when the rotational velocity of the x-ray source 12 or the linear velocity of the patient table is not accurately controlled. For example, the mechanics of either of these movements whether through wear, power fluctuations, or the like, may vary.

With reference to Figure 5A, interpolation function 62 is recalculated to function 94 to account for a ± 20% sinusoidal speed variation. Specifically:

$$\sum_m W_A(\phi_m) = 1, \text{ for } \phi_m = (r+m) \cdot 360 \quad (9)$$

$$\sum_m P(\phi_m) \cdot W_A(\phi_m) = 0 \quad (10),$$

where $P(\phi)$ is the table position relative to rotational angle ϕ . Although this satisfies the requirement for planar reconstructions, Figure 5B shows that the spatial resolution of curve 94 does not match the resolution 73 of curve 62. However, if the values of the weighting function $W(\phi)$ are remapped to $W(P(\phi))$, a constant spatial response can be maintained. This weighting is adjusted such that

$$\sum_m W_A(P(\phi_m)) = 1, \text{ for } \phi_m = (r+m) \cdot 360 \quad (11)$$

5

$$\sum_m P(\phi_m) W_A(P(\phi_m)) = 0 \quad (12).$$

10

With the new weighting function 98, a spatial response 100 of FIGURE 5C is substantially the same as the spatial response 73 of FIGURE 5B. In this manner, the interpolation function is utilized to correct for fluctuations in the speeds of relative movement of the source and patient.

15 Another application is to adjust the exposure of a subject that does not have a circularly uniform attenuation. As indicated above, a human patient commonly has an oval cross section. The synchronization control means 92 further controls a power supply 104 for the x-ray tube 20. The power supply adjusts the x-ray tube current or voltage generally in proportion to the mean attenuation path through the patient for each angular position of the x-ray tube. By varying the exposure in this manner, the quantum noise statistics of
20 the reconstructed volume can be made more uniform.

When the gantry rotation or table speed are varied disproportionately, the scan becomes non-helical. However, (as demonstrated above), a suitable reconstruction volume can still be attained. For higher attenuation projections, either the gantry rotation or the table movement is slowed to compensate for the higher quantum noise. Analogously, if the x-ray tube voltage, the filtration, or the x-ray tube current is
25 varied, a helical scan can still be performed. Specifically, the voltage filtration and/or current are increased for higher attenuative projections. The synchronization of these parameters may be either predetermined based on previous estimates or may be determined by estimates from earlier projections or scans of the same volume.

As discussed above, the views may be grouped into a group spanning 360° for 180° based
30 reconstructions. The energy level (kV) of the x-ray tube in another embodiment is varied or alternated between two levels. By continuously varying the kV with a prescribed high to low variation as shown in 112 of FIGURE 6A, two weighting functions (116, 118) can be applied to the respective projections to produce two sets of 180° based projections, both of which correspond to the same imaging plane. The average kV value for each ray in each set corresponds to either the high kV level or low kV level. Exactly 1-1/2 rotations
35 are required for each cycle from high kV to low kV back to high kV. The x-ray current 110 is varied counter cyclically to maintain the noise in both the high and low kV projections while minimizing the total exposure. Curve 114 identifies the high kV weighting function, $W_{hi}(R \cdot 180, \beta) = W_{hi}(\gamma, \beta)$.

With reference to FIGURE 6B, the weighting function applied by the interpolating means 46 shifts for the high and low kV portions. That is, curve 116 illustrates the preferred weighting function for the high kV
40 or voltage projection rays whereas the curve 118 illustrates the weighting function used with the low energy rays. These ray projections are recombined into two separate 180° based sets or groups of projections. In the illustrated embodiment, the beam width corresponds to about three rings of the helix and a reconstructed image or slice is obtained for every one and a half rings of the helix.

With reference to FIGURE 6C, the variation in weighting values for the extremes of the fan ($\beta = +/\beta_0$)
45 is illustrated for the high kV 180° based projection set. More specifically, weighting function curve 116 is shifted or swayed between curve 116a at one extreme ray of the fan and 116b at the other extreme ray of the fan. Analogous shifts are made for the weighting function 118 for the low kV projection set.

To increase the x-ray collection efficiency, a plurality of detectors are positioned adjacent to each other in the longitudinal direction. Positioning two detectors longitudinally enables the width of the radiation seen
50 by each detector to be selectively adjusted at the detector. Analogously, three or more detectors can be disposed in longitudinal alignment. This enables data along three interleaved spirals to be collected concurrently. In one embodiment, the three spirals of data cover the same volume with a greater sampling density. This is particularly advantageous in the dual energy modes described above. Alternately, the speed of the patient table is tripled such that the three sets of detector collect data with the same sampling density
55 but three times as fast.

Claims

1. A method of imaging including the step of: moving a radiation source (12) and a subject relative to each other so as to irradiate the subject along a generally spiral path; and characterised in that said method further includes the steps of collecting a plurality of views of image data, each view being identifiable by an angular position (ϕ, θ) around the subject and by an axial position (R) along a spiral; interpolating corresponding views collected over more than two revolutions along generally spiral paths; and reconstructing the interpolated views into a plurality of image representations corresponding to a plurality of parallel slices through the subject.
2. A method according to Claim 1 wherein the interpolating step includes interpolating with a cubic weighting function (66).
3. A method according to Claim 1 wherein the interpolating step includes interpolating with an n-lobe helical weighting function (70), where n is greater than or equal to 3.
4. A method according to Claim 3 wherein views taken at more than four longitudinal positions are interpolated with the n-lobe helical weighting function (70).
5. A method as set forth any preceding claim wherein the irradiating step includes irradiating the subject with radiation having at least two energy levels.
6. A method according to any preceding claim wherein the view collecting step includes collecting radiation from the source (12) which has traversed the subject with at least two arcs of radiation detectors (24), which arcs are displaced longitudinally.
7. A method according to any preceding claim wherein the reconstructing step includes reconstructing a plurality of views which span an angle less than or equal to 360° around the spiral.
8. A method according to any preceding claim wherein said generally spiral paths comprise first and second generally spiral paths, said second generally spiral path being different from the first but covering the same volume.
9. A method according to any preceding claim wherein each view represents rays of radiation extending in a fan-shaped pattern from an apex (28), each ray being identifiable by an angular position (ϕ, θ) of the view around the spiral and by an angular position (β, α) of the ray within the fan shaped view; and, wherein the interpolating step includes interpolating the rays within each view with an interpolating function (82, 84, 86, 88) selected in accordance with both the view angular position (ϕ, θ) and the ray angular position (β, α).
10. A method according to any preceding claim further including the steps of: monitoring cyclic movement of the regions of the subject; and, synchronizing the relative rotational movement between regions of the subject and the radiation source (12) with the cyclic movement.
11. A method of imaging, including the step of: moving a subject and a radiation source (12) such that the subject is irradiated along a first generally spiral path; characterised in that it further includes the steps of collecting a plurality of views of data each identifiable by its position (ϕ, θ) along said spiral path; interpolating longitudinally corresponding views with an interpolation function (66, 68, 70, 82, 84, 86, 88, 94, 98, 116, 118); and, reconstructing groups of views which nominally span less than 360° into a plurality of parallel planar image representations corresponding to a plurality of parallel slices of the subject.
12. A method according to Claim 11 wherein each view represents a plurality of rays of radiation extending in a fan-shaped pattern from an apex (28), each ray being identifiable by an angular position (ϕ, θ) of the view around the spiral and by an angle of the ray (β, α) within the view; and, wherein the interpolating step includes interpolating the rays within each view with an interpolating function (82, 84, 86, 88) selected in accordance with both the view angular position (ϕ, θ) and the ray angle (β, α).
13. A method according to Claim 11 or 12 wherein adjacent groups of views are generated with different energy radiation.

14. A method according to Claim 11, 12 or 13 further including: monitoring cyclic movement of regions of the subject; and, synchronizing relative rotational movement between the regions of the subject and the radiation source (12) with the cyclic movement of said regions.
- 5 15. A method according to Claim 11, 12, 13 or 14 wherein the interpolation function has a higher band width at selected view angular positions and a smaller band width at other selected view angular positions.
16. A method according to Claim 11, 12, 13, 14 or 15 further including the step of moving the subject and
10 radiation source (12) to irradiate the subject along a second spiral path different from the first but covering the same volume.
17. A method according to Claim 11, 12, 13, 14, 15 or 16 wherein the view collecting step includes collecting radiation from the source (12) which has traversed the sample with at least two arcs of
15 radiation detectors (24), which arcs are displaced longitudinally.
18. A method of imaging including the step of: moving a subject and a radiation source (12) such that the subject is irradiated along a generally spiral path; and characterised in that it further includes the steps of collecting a plurality of views of data, each view being defined by a plurality of rays of radiation
20 meeting at an apex (28) with each view being identifiable by an angular position of the apex (ϕ , θ) along a spiral; filtering rays within the views with each of a multiplicity of filter functions (82, 84, 86, 88) each filter function being selected in accordance with the angular position (ϕ , θ) of the view and an angular position (β , α) of the ray within the view; and reconstructing the views into a plurality of parallel image representations.
25
19. A method according to Claim 18 wherein the reconstructing step includes reconstructing groups of views which span about 180° of each planar image representation.
20. A method of imaging including: rotating a source of radiation (12) around a subject; characterised in that it further includes converting radiation which has traversed the subject into a plurality of views,
30 each view including a fan shaped array of radiation paths with an apex (28) of each fan shaped array disposed at an identifiable angular position (ϕ , θ) around the subject; monitoring for a preselected cyclic event in the subject; controlling rotational movement of the radiation source (12) to synchronize the source rotation and the monitored cyclic event; reconstructing the views into at least one image
35 representation.
21. A method of imaging as claimed in Claim 20 comprising: causing relative rotational and longitudinal movement between said subject and said source of radiation (12) such that the subject is irradiated along a generally spiral path.
40
22. A method according to Claim 20 or 21 further including operating on a plurality of views, each with a corresponding view angular position (ϕ , θ) with an interpolation function to create an interpolated view, and wherein the reconstructing step is performed on the interpolated views.
- 45 23. A method according to Claim 20, 21, 22 or 23 further including varying an energy output of the source of radiation (12) between at least two levels.
24. A method according to Claim 21 wherein the reconstructing step includes reconstructing a plurality of views collected over other than two revolutions around the spiral.
50
25. A method of imaging including the steps of: rotating a source of radiation (12) around an examination region (14); and characterised in that it further includes the steps of detecting radiation which has traversed the examination region (14) to collect a plurality of views of data, each view being identified by an angular position (ϕ , θ) around the examination region (14); filtering each view with one of a
55 plurality of filter functions (66, 68, 70, 82, 84, 86, 88, 94, 98, 116, 118) selected in accordance with the angular position (ϕ , θ) of the view around the examination region (14); and reconstructing the views into at least one image representation.

26. A method of imaging including the steps of: moving a radiation source (12) and a subject relative to each other such that the radiation source (12) irradiates the subject generally along a spiral; concurrently detecting radiation which has traversed the patient to collect views of data; filtering collected data views; reconstructing the filtered data views into a plurality of image representations representing parallel displaced planes; characterised in that at least two longitudinally spaced arcs of detectors (24) detect said radiation to collect views of data lying along at least two interleaved spiral paths.
27. A method according to Claim 26 wherein each data view is defined by a plurality of rays in a fan shaped array and wherein in the filtering step, a filtering function (82, 84, 86, 88, 116, 118) is weighted in accordance with an angle of the view (ϕ , θ) around the subject and an angle of the ray (β, α) within each view.
28. A method according to Claim 26 or 27 wherein in the irradiating step, the energy of the radiation source beam is varied between at least two energy levels.
29. A method of imaging including the steps of: rotating a source of radiation (12) around a subject in an examination region (14); detecting radiation which has traversed the subject to collect views of data, each view having an apex (28) at an identifiable angle (ϕ , θ) around the subject and each view including a fan shaped array of radiation beams which have traversed the patient; filtering the views, using a filter function (116, 118); and reconstructing the views into at least one image representation; characterised in that it further includes while the source of radiation is rotating, varying an energy of the radiation source (12) between at least two energy levels.
30. A method according to claim 29 further including means (32) for advancing the subject through the examination region (14) with a substantially constant velocity.
31. A method according to claim 29 or 30 further including varying the filter function (62, 66, 68, 70, 82, 84, 86, 88, 94, 98, 116, 118) in accordance with at least one of the view angle (ϕ , θ) and the ray angle (β, α).
32. A method according to claim 29, 30 or 31 wherein in the radiation detecting step, views of data are collected which lie along at least two spiral paths around a common imaged volume of the subject.
33. A method according to claim 30, 31 or 32 wherein the reconstructing step includes reconstructing a plurality of views which span less than 360° around the spiral.
34. A method according to claim 29, 30, 31, 32 or 33 further including monitoring an angular position (ϕ) of the radiation source (12) around the examination region and wherein the energy of the radiation source (12) is varied in accordance with the monitored angular position (ϕ) of the radiation source (12).
35. A method of imaging including the steps of: rotating a source of radiation (12) around an examination region (14); moving a subject through the examination region (14); characterised in that it further includes the steps of monitoring at least one of (i) the rotation of the radiation source (12), (ii) longitudinal movement of the subject, and (iii) an energy of the radiation source (12); converting radiation which has traversed the subject into a plurality of views, each view including data collected from a fan shaped array of radiation rays with an apex (28) of each array disposed at an identifiable angular position (ϕ , θ) around the examination region (14); filtering each view with a filter function (62, 66, 68, 70, 82, 84, 86, 88, 94, 98, 116, 118); controlling at least one of the rotation of the radiation source (12), the longitudinal movement of the subject, an energy of the radiation source (12), the longitudinal movement of the subject, an energy of the radiation source (12), and the filter function (62, 66, 68, 70, 82, 84, 86, 88, 94, 98, 116, 118) in accordance with the monitoring step; and reconstructing the filtered views into at least one image representation.
36. An imaging apparatus including: means (20, 32) for moving a radiation source (12) and a subject relative to each other so as to irradiate the subject along a generally spiral path; and an arc of radiation detectors (24) for receiving radiation which has traversed the subject; characterised in that it further includes means (44) for assembling radiation detected by the radiation detectors (24) into a plurality of views, each view being identifiable by an angular position (ϕ , θ) around the subject and an axial

position R along a spiral path; interpolating means (46) for interpolating angularly corresponding views collected over more than two revolutions around the generally spiral paths; reconstructing means (54) for reconstructing the interpolated views into a plurality of image representations; and memory means (56) for storing the plurality of image representations.

5

37. An imaging apparatus including: means (20, 32) for moving a subject and a radiation source (12) such that the subject is irradiated along a generally spiral path; and at least one arc of radiation detectors (24) for detecting radiation from the source (12) which has traversed the subject; characterised in that it further includes means (44) for assembling detected radiation into a plurality of views, each view having data generated from radiation that traversed the subject along a plurality of rays, each ray having an identifiable angular position (β, α) within a view and each view being identifiable by an angular position (ϕ, θ) around a spiral path and a longitudinal position R along the spiral path; filtering means (46) for filtering views identified by the same angular position (β, α) with a filter function (82, 84, 86, 88, 116, 118); reconstructing means (54) for reconstructing groups of views, which nominally span 180° , into a plurality of image representations; and memory means (56) for storing the plurality of image representations.

38. An imaging apparatus including: a source of radiation (12); means (20) for rotating the source of radiation (12) around a subject; and at least one arc of radiation detectors (24) for converting radiation from the source (12) which has traversed the subject into a plurality of views, each view including data converted from a fan shaped array of radiation rays with an apex (28) of each fan shaped array disposed at an identifiable angular position (ϕ, θ) around the subject; characterised in that it further includes subject monitoring means (90) for monitoring a preselected cyclic movement of said subject; controlling means (92) operatively connected to the radiation source rotating means (20) and the monitoring means (90) for controlling relative rotation of the source (12) in accordance with the monitored cyclic movement; reconstructing means (54) for reconstructing the views into at least one image representation; and memory means (56) for storing the at least one image representation.

39. An imaging apparatus including: subject supporting means (30) for supporting a subject in an examination region (14); a radiation source (12) for irradiating a portion of the subject in the examination region (14) with penetrating radiation; means (20) for rotating the radiation source (12) around the examination region (14); means (32) for longitudinally advancing the patient supporting means (30) through the examination region (14) at a generally constant velocity; means (24) for detecting said radiation; means (44) for assembling the detected radiation into a plurality of views; filtering means (46) for filtering the views; reconstructing means (54) for reconstructing the filtered views into a plurality of image representations; and memory means (56) for storing the image representations; characterised in that said means (24) for detecting said radiation comprises at least two parallel arcs of radiation detectors (24) disposed generally parallel to a path of radiation from said source (12) for concurrently detecting radiation which has traversed the subject along at least two longitudinally spaced arcs; and each view is identifiable by an angular position (ϕ, θ) relative to the subject and a longitudinal position R along at least two interleaved spiral paths around the subject.

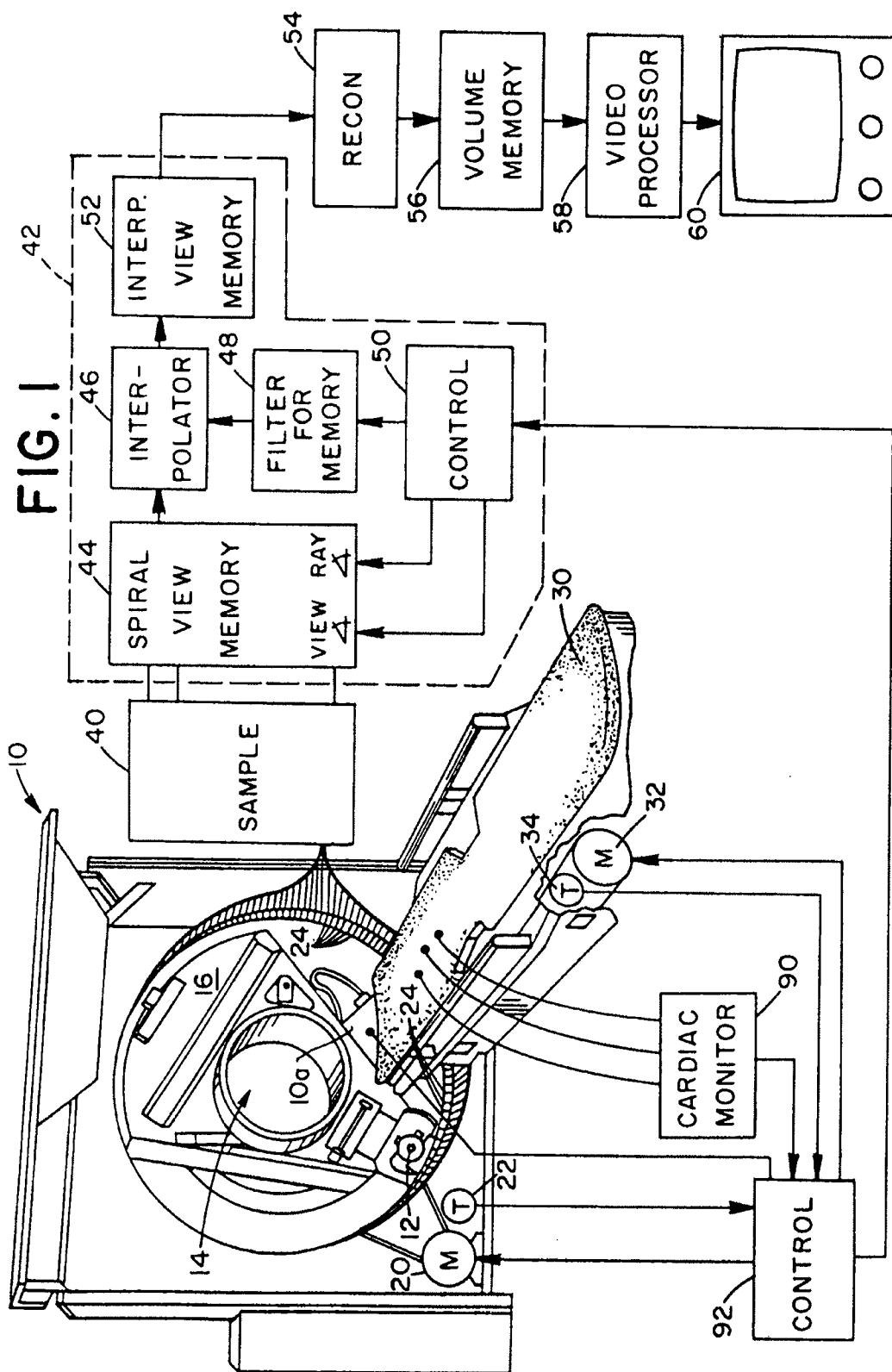
40. An imaging apparatus including: a source of radiation (12); means (20) for rotating the source of radiation (12) around an examination region (14); radiation source energy control means (104) for controlling an energy output of the radiation source (12); at least one arc of radiation detectors (24) for detecting rays of radiation which have traversed the subject; means (44) for assembling detected radiation into a plurality of views, each view representing rays meeting at an apex (28) at an identifiable angle (ϕ, θ) within the examination region (14, 214); reconstruction means (54) for reconstructing the views into an image representation; characterised in that the radiation source energy controlling means (104) causes the radiation source energy to vary between at least two energy levels.

41. An imaging apparatus including: a source of radiation (12); radiation source energy control means (104) for controlling an energy of radiation generated by the radiation source (12); means (16, 20) for rotating the radiation source (12) around an examination region (14); means (32) for advancing a patient supporting means (30) longitudinally through the examination region; at least one arc of radiation detectors (24) for detecting rays of radiation from the source (12) which has traversed the examination region (14); characterised in that it further includes means for organizing radiation (44) detected by the radiation detectors (24) into a plurality of views, each view representing a fan shaped array of radiation

rays with an apex (28) of the array disposed at an identifiable angular position (ϕ , θ) within the examination region (14); filtering means (46) for filtering the views with a filter function (66, 68, 70, 82, 84, 86, 88, 94, 98, 116, 118); monitoring means (22, 34, 104) for monitoring at least one of a speed of radiation source rotation, a speed of patient supporting means (30) longitudinal advancement, and an energy of the radiation source; means (50, 92) operatively connected with the monitoring means (22, 34, 104) for controlling at least one of the speed of rotation of the radiation source (12), the speed of longitudinal advancement of the patient supporting means (30), the energy of the radiation source (12), and/or selecting the filter function (66, 68, 70, 82, 84, 86, 88, 94, 98, 116, 118); reconstructing means (54) for reconstructing the views into image representations; and memory means (56) for storing the image representations.

42. An imaging apparatus including: a source of radiation (12); means (16, 20) for rotating the source of radiation (12) around an examination region (14); means for determining an angular position (ϕ , θ) of the source of radiation (12) around the examination region (14); at least one arc of radiation detectors (24) for detecting radiation from the radiation source (12) that has traversed the examination region (14); means (44) for assembling the detected radiation into a plurality of views; filtering means (52) for filtering each view with a filter function (62, 66, 68, 70, 82, 84, 86, 88, 94, 98, 116, 118); reconstructing means (54) for reconstructing the views into at least one image representation; memory means (56) for storing the at least one image representation; characterised in that each view is identifiable by an angular position (ϕ , θ) within the examination region (14) and in that said apparatus comprises filter function selecting means (48) for selecting a filter function corresponding to the angular position (ϕ , θ) of each view.

43. An imaging apparatus including: a source of penetrating radiation (12); means (16, 20) for rotating a source of radiation (12) around an examination region (14); means (32) for advancing a subject through the examination region (14); means (32) for advancing a subject through the examination region; at least one arc of radiation detectors (24) for detecting radiation from the radiation source (12) that has traversed the examination region (14); means (44) for organizing the collected radiation into a plurality of views of data; filtering means (46) for filtering data representing each ray of each view with a filter function; reconstructing means (54) for reconstructing the image representations from the views; and memory means (56) for storing the image representations, characterised in that each view represents a plurality of rays of radiation extending in a fan shaped array from an apex at an identifiable angle (ϕ , θ) around the examination region (14); and in that said filter function is selected in accordance with the identifiable angle (ϕ , θ) of the view within the examination region and an angle (β, α) of each ray within the corresponding view.



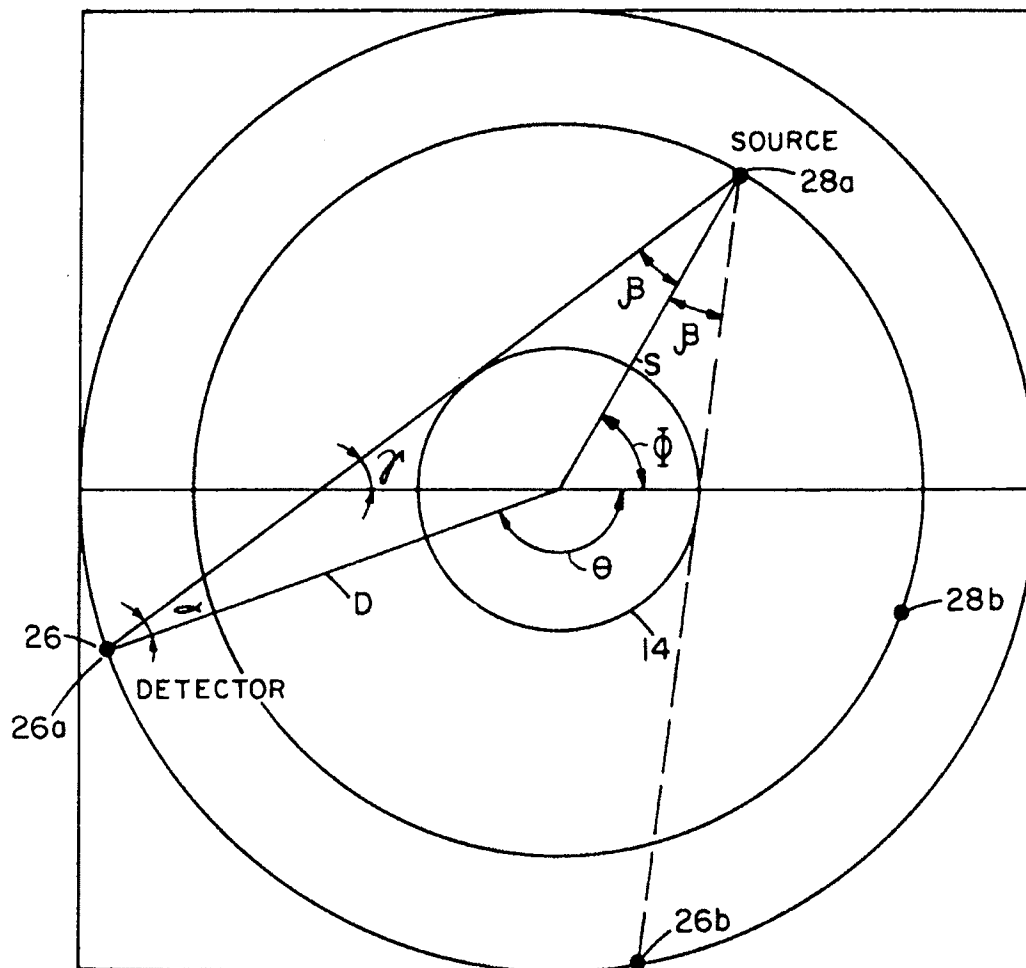
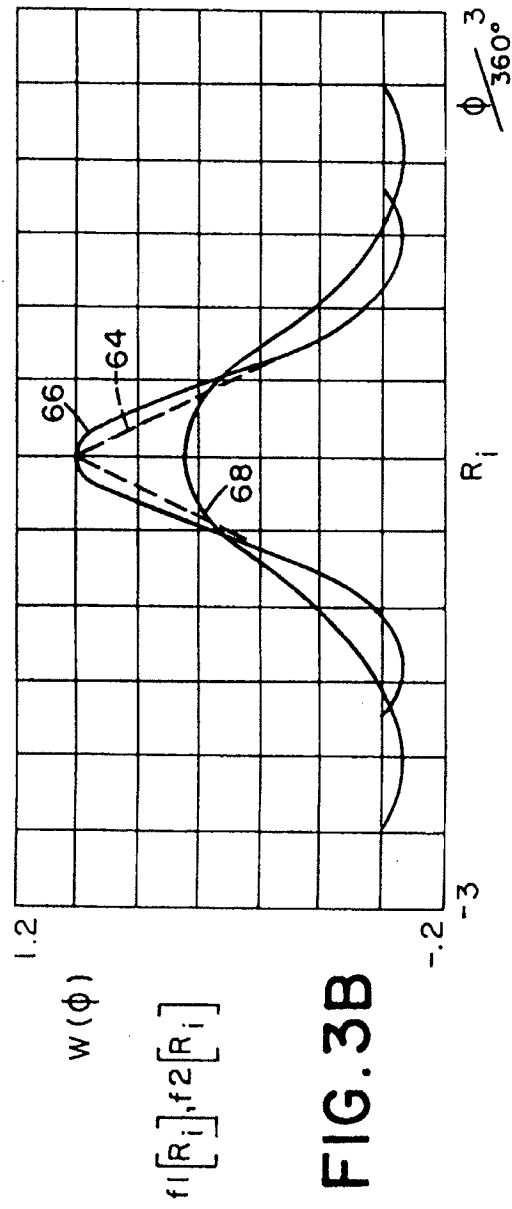
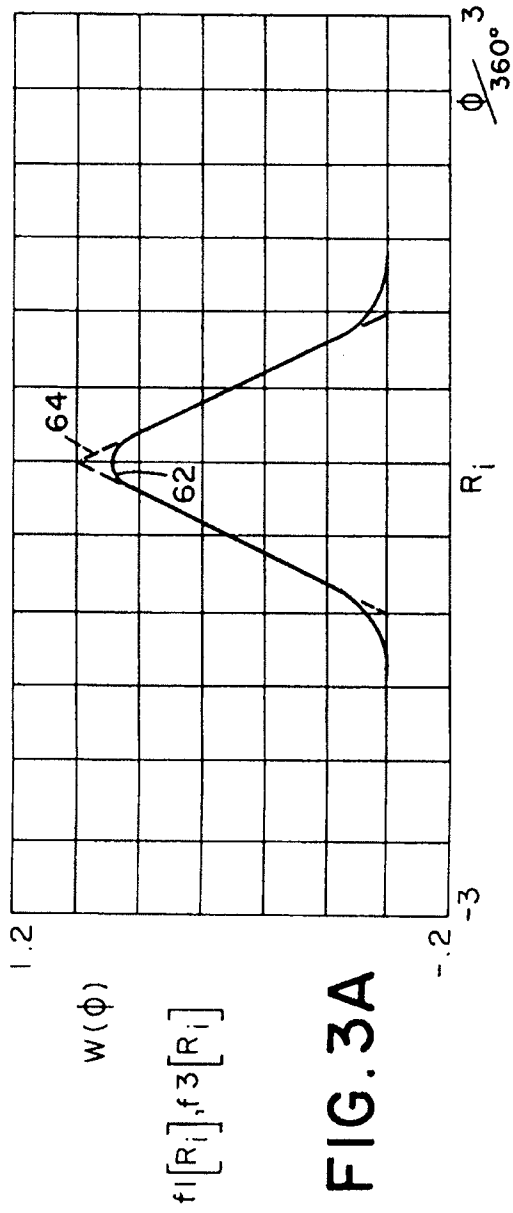
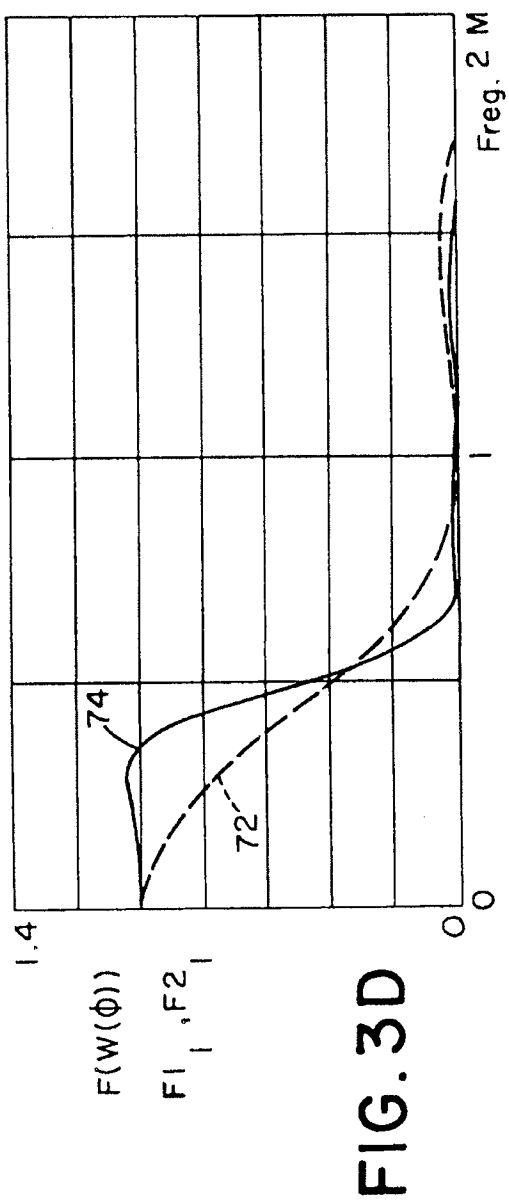
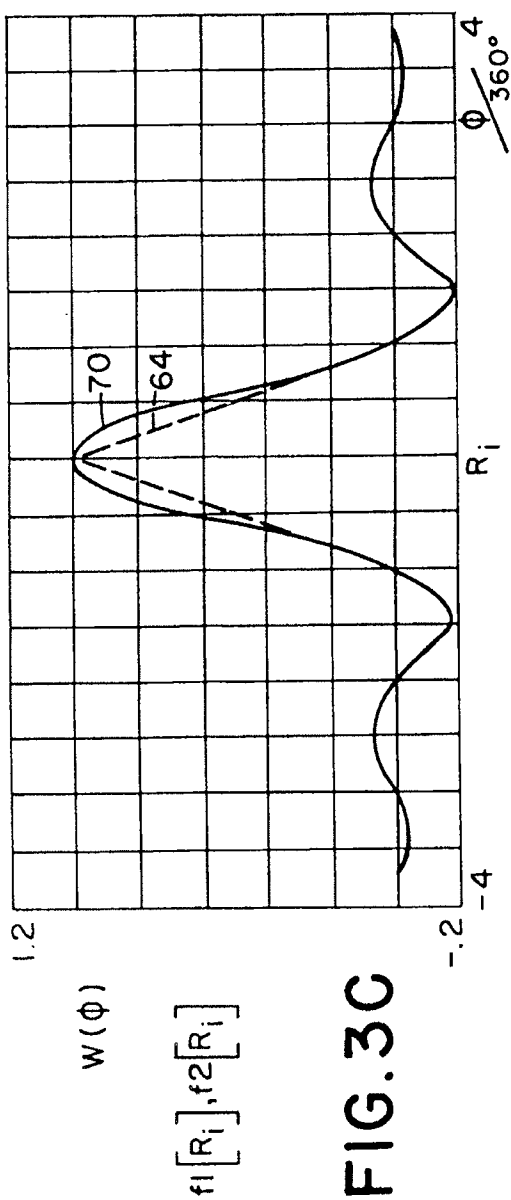
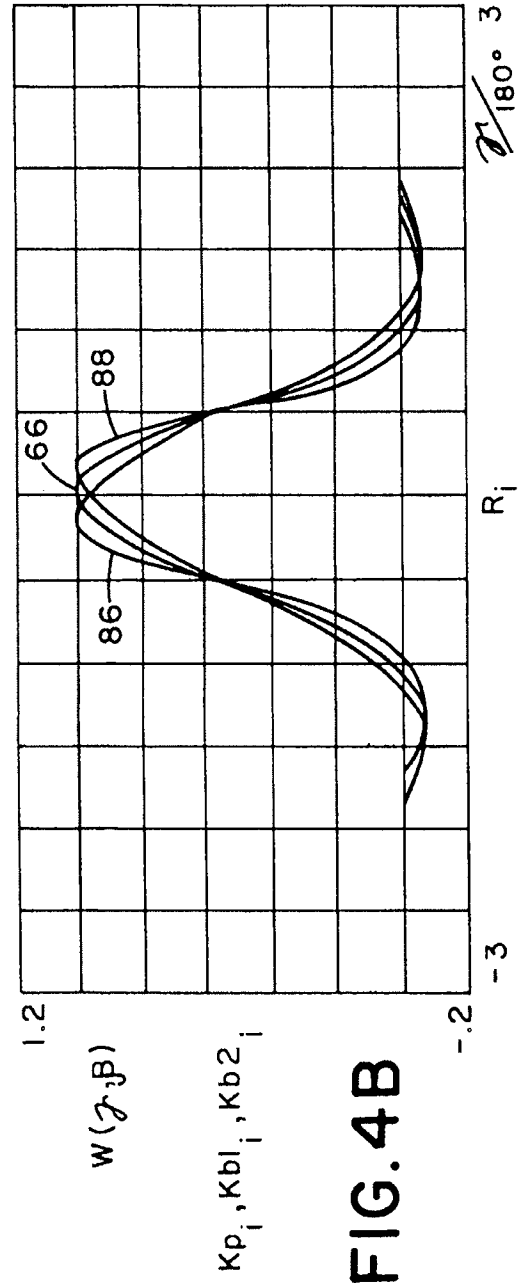
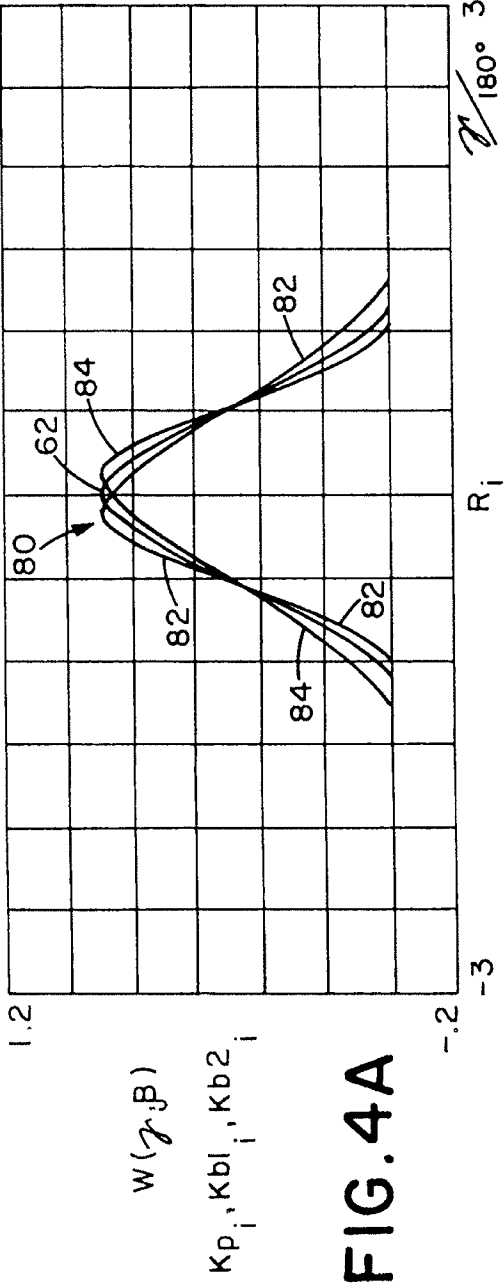
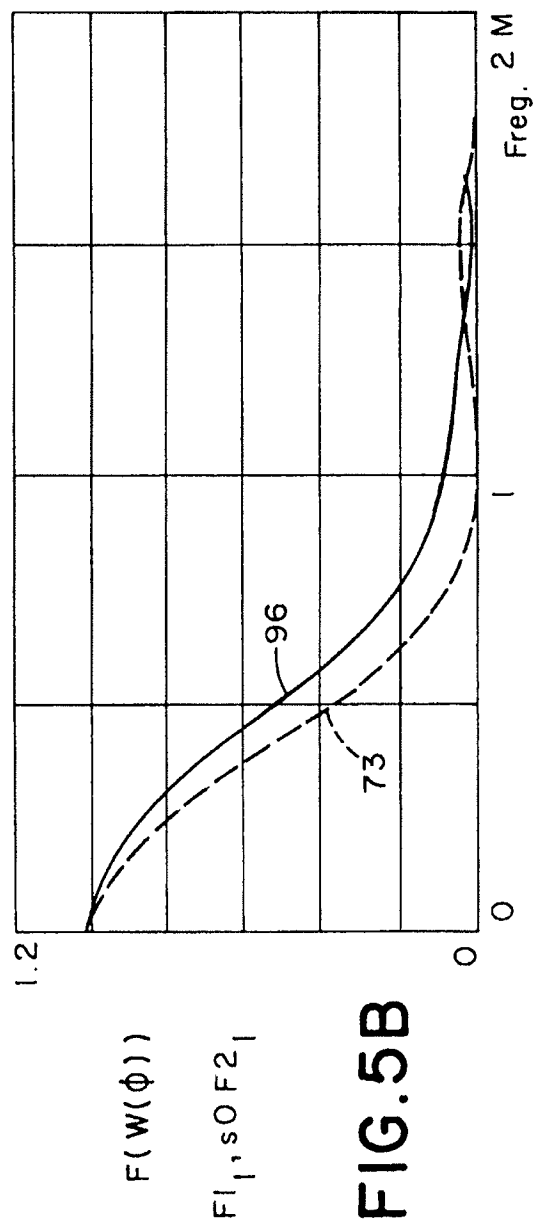
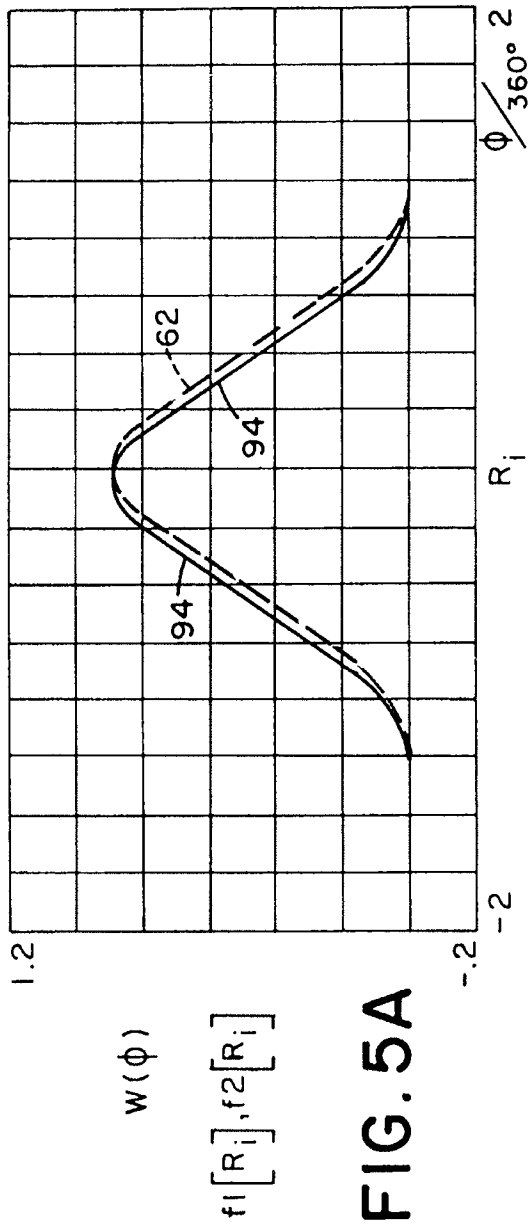


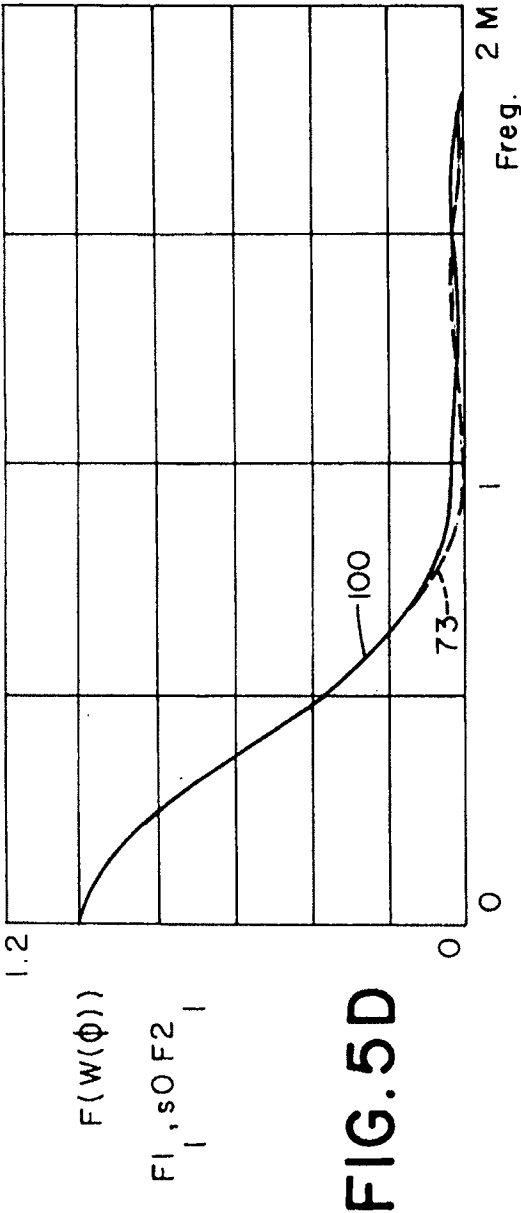
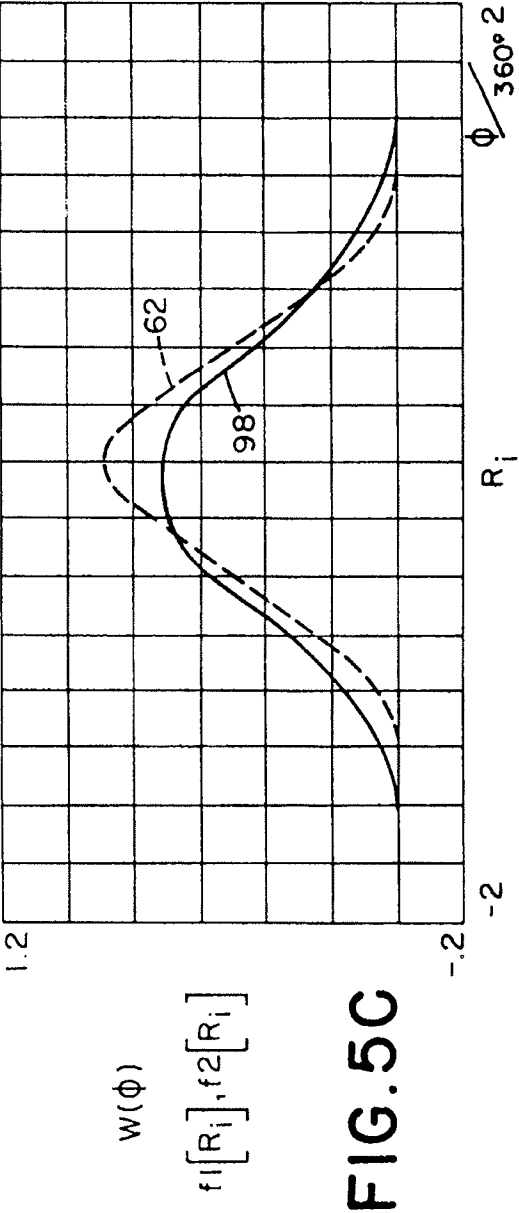
FIG. 2

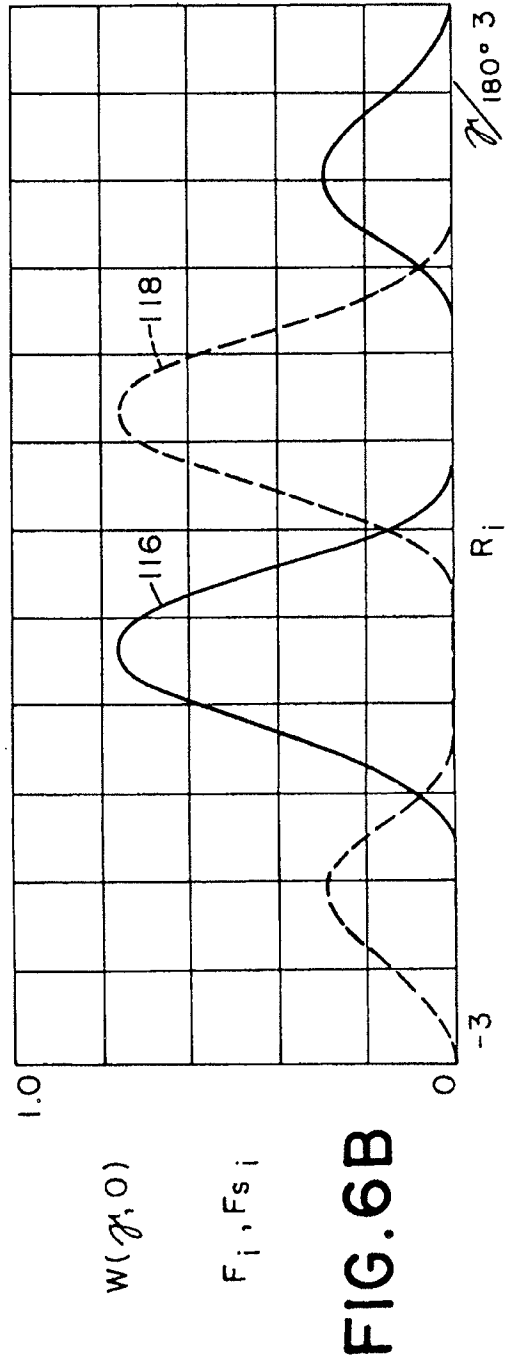
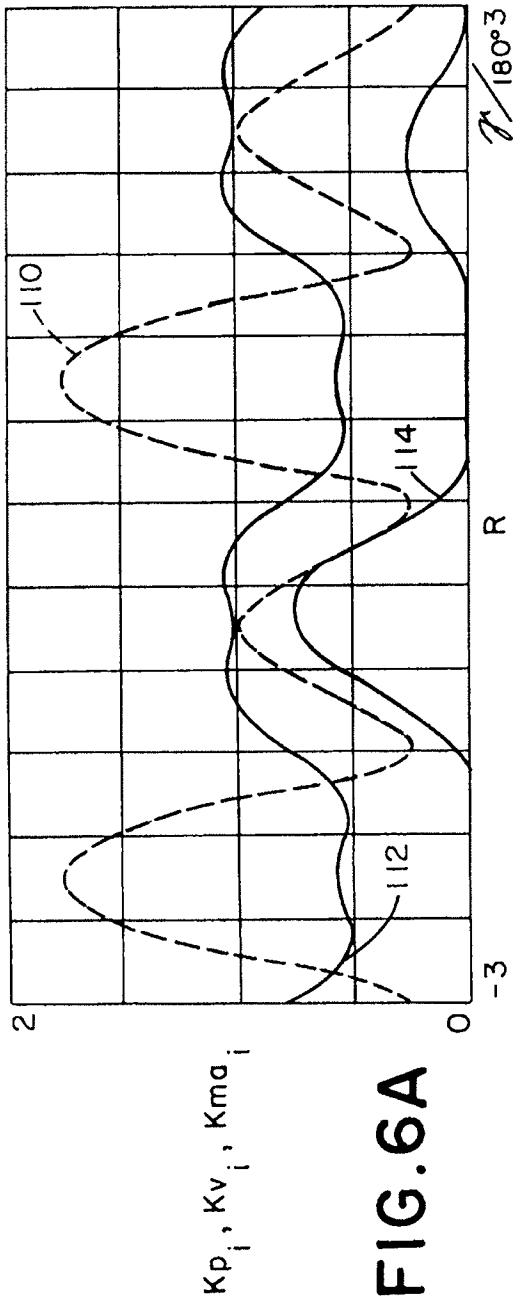












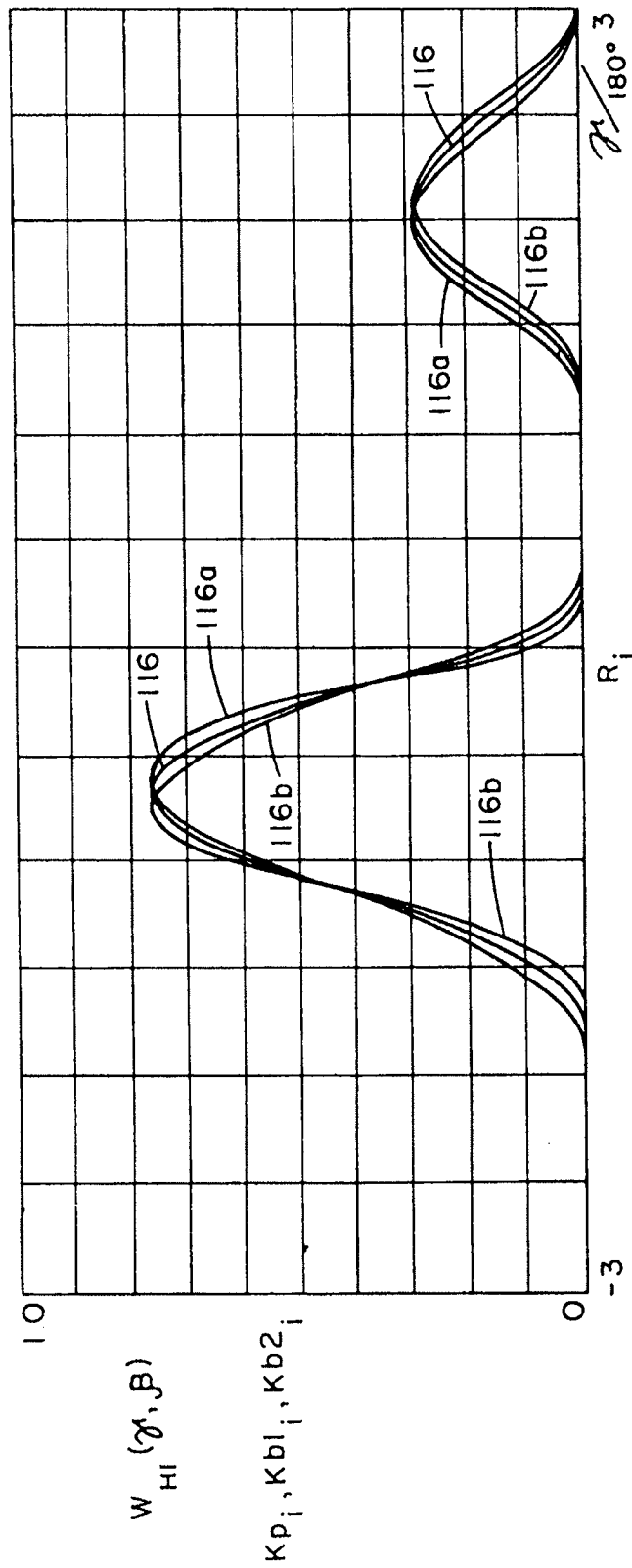


FIG. 6C